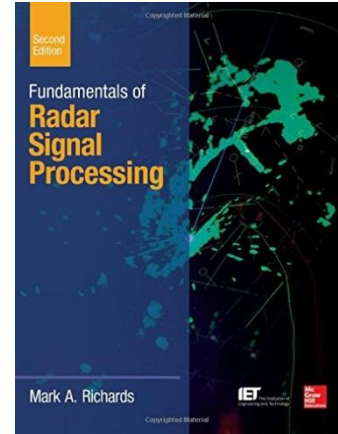


# Errata for all Printings

## ***Fundamentals of Radar Signal Processing, second edition***

Mark A. Richards

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*The author wishes to thank the many students and readers who will, no doubt, help to identify errata in the text. The responsibility for all errors, both those that have been found and those yet to be found, lies entirely with the author.*

| <b><i>Page</i></b> | <b><i>Location on Page</i></b> | <b><i>Correction</i></b>   |
|--------------------|--------------------------------|--|
| 59                 | Table 2.3                      | <ul style="list-style-type: none"> <li>In the “comment” column for the Weibull case, change “Can have longer “tail” than previous cases.” to “Can model long-tailed or “spiky” data.”</li> <li>In the “comment” column for the Weibull case, change “ “Tail” is longest of previous cases.” to “Can model long-tailed or “spiky” data.”</li> </ul>   |
| 60                 | 1 <sup>st</sup> line of text   | <ul style="list-style-type: none"> <li>Change “chi-square and K distributions.” to “chi-square distributions of arbitrary order and K distributions.”</li> </ul>   |
| 62                 | Table 2.4                      | <p>Several corrections to table entries:</p> <ul style="list-style-type: none"> <li>Nonfluctuating case, “Comment” column: Change to “Also nonfluctuating model, one parameter changed: <math>\bar{\sigma} \rightarrow \sqrt{\bar{\sigma}}</math>”</li> <li>Central chi degree 4 case: Correct the expression for the mean to read <math display="block">\bar{\zeta} = \frac{3}{4} \sqrt{\frac{\pi \bar{\sigma}}{2}}</math></li> <li>Central chi, degree <math>2m</math> case: Correct the expression for the mean to read <math display="block">\bar{\zeta} = \frac{\Gamma(m+0.5)}{\Gamma(m)} \sqrt{\frac{\pi \bar{\sigma}}{m}}</math></li> <li>Rice case, “RCS Model Name” column: change “chi-square” to just “chi”.</li> <li>Rice case: delete the subscript “1” from the <math>e^{-a^2}</math> term in the expression for the mean <math>\bar{\zeta}</math>.</li> <li>Rice case, “Comment” column: Change “<math>{}_1F_1(x)</math>” to <math>{}_1F_1(\alpha, \beta, x)</math>.</li> <li>Weibull case: In the expression for <math>\text{var}(\zeta)</math>, change the term <math>B^{-1/2C}</math> to <math>B^{-1/C}</math>.</li> <li>Log-normal case: Change the exponential term in the formula for the PDF from <math>\exp\left[-2\ln^2\left(\zeta/\sqrt{\sigma_m}\right)^2/s^2\right]</math> to <math>\exp\left[-4\ln^2\left(\zeta/\sqrt{\sigma_m}\right)^2/s^2\right]</math>.</li> </ul> |

| <b>Page</b> | <b>Location on Page</b>        | <b>Correction</b>   |
|-------------|--------------------------------|---|
| 63          | Eq. (2.56)                     | <p>The left parenthesis should appear after the symbol <math>\Omega</math> in the first line, not before it. The corrected equation is</p> $\begin{aligned}\bar{y}(t) &= \sum_{n=-M}^M A e^{j\Omega(t-2(R_0+n\Delta x \sin \theta)/c)} \\ &= A e^{j\Omega(t-2R_0/c)} \sum_{n=-M}^M e^{-j4\pi n\Delta x \sin \theta F/c}\end{aligned}$   |
| 82          | Third line before Eq. (2.84)   | <p><math>P_0</math> should be <math>P_o</math> (the subscript should be an italic lower-case letter ‘o’ instead of a non-italic numeral zero).</p>  |
| 87          | Second line after Eq. (2.97)   | <p>The term <math>-(1+\beta_v)4\pi/\lambda R_0</math> should instead be <math>-(1+\beta_v)(4\pi/\lambda)R_0</math>, i.e. the <math>R_0</math> belongs in the numerator.</p>   |
| 114         | First paragraph and Eq. (3.9)  | <p>This section is conflating unambiguous range and the beginning of the blind range zone. Unambiguous range should be defined based on the periodicity of the range response. Consequently, Eq. (3.9) should be simply</p> $R_{ua} = \frac{cT}{2} = \frac{c}{2PRF}$ <p>and the 2<sup>nd</sup> and 3<sup>rd</sup> sentences in the first paragraph should be replaced with “In particular, the maximum range from which an echo of the leading edge can be received before the next pulse is transmitted is the <i>unambiguous range</i>. It must satisfy <math>2R_{ua}/c = T</math>, so”</p> |
| 166         | Eq. (4.79)                     | <p>The lower limit on the summation should have <math>M</math> instead of <math>m</math>. The corrected equation is</p> $A(t, 0) = \begin{cases} \sum_{m=-(M-1)}^{M-1} (M -  m ) \left(1 - \frac{ t - mT }{\tau}\right) &  t - mT  < \tau \\ 0 & \text{elsewhere} \end{cases}$  |
| 230         | Last line preceding Eq. (5.29) | <p>Change <math>(\sigma_n^2 \gg \sigma_n^2)</math> to <math>(\sigma_c^2 \gg \sigma_n^2)</math></p>  |
| 301         | Eq. (6.19)                     | <p>The left hand side of the equation is the complementary error function, not the error function itself. The corrected equation is</p> $\operatorname{erfc}(x) \equiv \frac{2}{\sqrt{\pi}} \int_x^{+\infty} e^{-t^2} dt = 1 - \operatorname{erf}(x)$   |

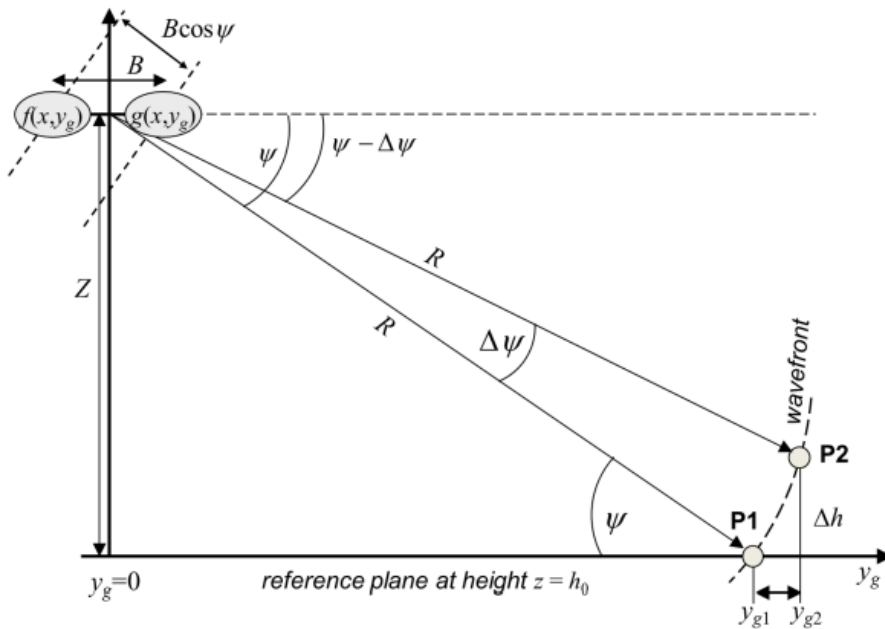
| <b>Page</b> | <b>Location on Page</b>                                     | <b>Correction</b>   |
|-------------|---|---|
| 301         | Eqs. (6.20) and (6.21), and last line of text before (6.20) | <p>The variable representing noise power is <math>\sigma_w^2</math>, not <math>\beta^2</math>. The corrected text and equations are:</p> <p>text: “With the change of variables <math>t = Y / \sqrt{2N\sigma_w^2}</math>, Eq. (6.17) can be written as”</p> $(6.20): \alpha = P_{FA} = \frac{1}{\sqrt{\pi}} \int_{T/\sqrt{2N\sigma_w^2}}^{+\infty} e^{-t^2} dt = \frac{1}{2} \left[ 1 - \operatorname{erf} \left( \frac{T}{\sqrt{2N\sigma_w^2}} \right) \right]$ $(6.21): T = \sqrt{2N\sigma_w^2} \operatorname{erf}^{-1}(1 - 2P_{FA})$ |
| 307         | 3 <sup>rd</sup> line in section 6.2.1                       | change $KT$ to $kT$   |
| 311         | Eqs, (6.40) and (6.42)                                      | Change $\mathbf{E}$ to $E$ in the exponential in both equations.  |
| 312         | 2 <sup>nd</sup> line of text before Eq. (6.45)              | Change $\sigma_w^2$ to $\sigma_w$ .   |
| 313         | First line of text after Eq. (6.48)                         | Change $E\sigma_w^2 \sim N(E, E\beta^2)$ to $\tilde{\mathbf{m}}^H \mathbf{y} \sim N(E, E\sigma_w^2)$ . Also, in the next two lines of text, change $N(E, E\beta^2/2)$ to $N(E, E\sigma_w^2/2)$ , and $N(0, E\beta^2/2)$ to $N(0, E\sigma_w^2/2)$ .  |
| 313         | Text before and after Eq. (6.49)                            | Replace the last two sentences preceding (6.49) in their entirety with the following: “For a particular target and thus a particular value of $\theta$ , the real and imaginary parts of $\tilde{\mathbf{m}}^H \mathbf{y}$ are distributed respectively as $N(E \cos \theta, E\beta^2)$ and $N(E \sin \theta, E\beta^2)$ . Regardless of the value of $\theta$ , the PDF of $z =  \tilde{\mathbf{m}}^H \mathbf{y} $ is then”  |
| 323         | Footnote 12   | <p>The definition of the incomplete gamma function in Eq. (6.80) on p. 322 is <i>not</i> consistent with that used in the MATLAB® <code>gammainc</code> function. Following is the correct relationship:</p> $I(\mu, M) = \text{gammainc}(\mu \sqrt{M+1}, M+1)$ <p>It follows that the right hand side of Eq. (6.79) is expressed in MATLAB as</p> $1 - \text{gammainc}(T, N),$ <p>a simpler expression that I’ll probably switch to in the next edition.</p>   |

| Page    | Location on Page              | Correction  |
|---------|-------------------------------|---|
| 323     | Eq. (6.85)                    | The denominator of the first term on the right-hand side should be the product $N\chi$ , not $N_x$ . The corrected equation is<br>$p_{z'}(z' H_1) = \left(\frac{z'}{N\chi}\right)^{\frac{N-1}{2}} \exp(-z' - N\chi) I_{N-1}(2\sqrt{N\chi z'})$  |
| 323     | Eq. (6.86)                    | The denominator of the first term in the integral on the right-hand side should be the product $N\chi$ , not $N_x$ . The corrected equation is<br>$P_D = \int_T^\infty \left(\frac{z'}{N\chi}\right)^{\frac{N-1}{2}} \exp(-z' - N\chi) I_{N-1}(2\sqrt{N\chi z'}) dz'$ $= Q_M(\sqrt{2N\chi}, \sqrt{2T}) + e^{-(T+N\chi)} \sum_{r=2}^N \left(\frac{T}{N\chi}\right)^{\frac{r-1}{2}} I_{r-1}(2\sqrt{N\chi T})$   |
| 324     | Eq. (6.87)                    | The value 5.54 in the second line of the equation should be changed to 4.54. The corrected equation line is<br>$\chi_1 = -5\log_{10} N + \left[6.2 + \left(\frac{4.54}{\sqrt{N+0.44}}\right)\right] \cdot \log_{10}(A + 0.12AB + 1.7B) \text{ dB}$  |
| 330     | Table 6.1, "Case 4" entry     | This is not an error, but for improved clarity, change the $P_D$ equation from<br>$\left\{ c^N \sum_{k=0}^N \frac{N!}{k!(N-k)!} \left(\frac{1-c}{c}\right)^{N-k} \right\} \left\{ \sum_{l=0}^{2N-1-k} \frac{e^{-cT} (cT)^l}{l!} \right\}, \quad T > N(2-c)$ $1 - \left\{ c^N \sum_{k=0}^N \frac{N!}{k!(N-k)!} \left(\frac{1-c}{c}\right)^{N-k} \right\} \left\{ \sum_{l=2N-k}^{\infty} \frac{e^{-cT} (cT)^l}{l!} \right\}, \quad T < N(2-c)$ to<br>$c^N \sum_{k=0}^N \left( \sum_{l=0}^{2N-1-k} \frac{e^{-cT} (cT)^l}{l!} \right) \frac{N!}{k!(N-k)!} \left(\frac{1-c}{c}\right)^{N-k}, \quad T > N(2-c)$ $1 - c^N \sum_{k=0}^N \left( \sum_{l=2N-k}^{\infty} \frac{e^{-cT} (cT)^l}{l!} \right) \frac{N!}{k!(N-k)!} \left(\frac{1-c}{c}\right)^{N-k}, \quad T < N(2-c)$ |
| 334     | Table 6.3                     | The correct value of $P_C$ in the last row ( $p = 10^{-6}$ ) is $6.0 \times 10^{-12}$ , not $6.0 \times 10^{-10}$ .   |
| 450     | Equation (8.7)                | The middle line of this equation should be changed to<br>$= e^{j\Omega t} e^{-j4\pi R/\lambda} \sum_{n=-M}^{+M} \exp[j2\Omega n d \sin \theta/c]$   |
| 489-490 | Equation (8.78) and Fig. 8.38 | Eq. 8.78 does not follow from Fig. 8.38. The correction involves a change to the figure and several scattered text changes to these two pages. Rather than try to list each individual change, at the end of this errata list I have included an update to the entire affected part of these two pages.   |

| <b>Page</b> | <b>Location on Page</b>                        | <b>Correction</b>   |
|-------------|--|---|
| 563         | 2 <sup>nd</sup> line of text before Eq. (A.45) | Change $N(x; \sigma\mu_i, \sigma^2)$ to $N(x; \sigma\mu_i, \sigma^2)$ |
| 571         | 1 <sup>st</sup> line of text                   | Change $\mu$ to $\boldsymbol{\mu}$ (boldface to indicate a vector)    |
| 571         | Last line of text before Eq. (A.83)            | Change “(A.92)” to “(A.81)”.  |
|             |  | <i>Your Erratum Here!</i>   |

**Correction to portions of Section 8.6.1, "The Effect of Height on a SAR Image", beginning p. 489 (second edition) or p. 437 (first edition). Includes corrections to text and equations, and modification of Fig. 8.38.**

NOTE: Equation numbers correspond to second edition; in the first edition, they are less by 3, i.e. Eq. (8.75) here and in the second edition is Eq. (8.72) in the first edition.



**Figure 8.38:** Geometry for interferometric height estimation.

Now consider the two scatterers **P1** and **P2** at ground ranges  $y_{g1}$  and  $y_{g2}$  as illustrated in Fig. 8.38. Both are at the same slant range  $R$ , but one is at an elevation  $z = h_0$  relative to some unknown reference plane while the other is at an elevation  $z = h_0 + \Delta h$ . They are observed from two distinct radar apertures at an altitude  $z = h_0 + Z$  and separated horizontally by a *baseline*  $B$ .<sup>8</sup>

<sup>8</sup> The results here are generalized to include use of a common transmit aperture and two independent receive apertures in (Richards, 2013). Both one- and two-transmitter versions of IFSAR are of practical importance.

**Correction to portions of Section 8.6.1, “The Effect of Height on a SAR Image”, beginning p. 489 (second edition) or p. 437 (first edition). Includes corrections to text and equations, and modification of Fig. 8.38.**

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Each aperture independently transmits a radar waveform, receives the data, and forms a complex SAR image of the scene; these images are denoted by  $f(x, y_g)$  and  $g(x, y_g)$ . The baseline should be orthogonal to the flight path; therefore the direction of the aircraft motion is into the page.<sup>9</sup> The radar range is great enough that the incoming wavefront can be considered planar. If the depression angle from the middle of the baseline to **P1** is  $\psi$ , the difference in range to the two aperture phase centers is well approximated as  $B \cos \psi$ . The difference in received phase at the two apertures then becomes, using Eq. (8.74)

$$\phi_{fg} \equiv \phi_f - \phi_g \approx -\frac{4\pi}{\lambda} B \cos \psi \quad (8.75)$$

Now consider scatterer **P2**, having the same slant range as **P1** but elevated by  $\Delta h$  meters. Because the radar measures time delay and thus slant range, the echo from **P2** will be indistinguishable from that of **P1**. Assuming an approximately planar wavefront at range  $R$ , Fig. 8.38 shows that the difference in ground coordinates is approximately

$$y_{g2} - y_{g1} \approx \Delta h \tan \psi \quad (8.76)$$

Because basic SAR images are two-dimensional, **P2** will be imaged at ground range  $y_{g1}$ .<sup>10</sup> The imaging of the elevated scatterer at an incorrect ground range coordinate is termed *foreshortening* or *layover* because the scatterer appears to have been shifted toward the radar. As illustrated, the layover is only in the range coordinate. In squinted operation, layover occurs in both range and cross-range; details are given in (Sullivan, 2000) and (Jakowatz et al., 1996).

The difference in the depression angle from the center of the IFSAR baseline to **P2** versus the angle to **P1** caused by the height difference  $\Delta h$  can be found by differentiating Eq. (8.75) with respect to the grazing angle:

<sup>9</sup> The two apertures could also be displaced vertically, with similar results.

<sup>10</sup> SAR images are naturally formed in the slant plane, but are usually projected into the ground plane for display.

**Correction to portions of Section 8.6.1, “The Effect of Height on a SAR Image”, beginning p. 489 (second edition) or p. 437 (first edition). Includes corrections to text and equations, and modification of Fig. 8.38.**

NOTE: Equation numbers correspond to second edition; in the first edition, they are less by 3, i.e. Eq. (8.75) here and in the second edition is Eq. (8.72) in the first edition.

$$\frac{d\phi_{fg}}{d\psi} = \frac{4\pi}{\lambda} B \sin \psi \Rightarrow \Delta\psi = \frac{\lambda}{4\pi B \sin \psi} \Delta\phi_{fg} \quad (8.77)$$

This equation states that a change in the *interferometric phase difference* (IPD) of  $\Delta\phi_{fg}$  implies a change in depression angle to the scatterer of  $\Delta\psi$  radians. To relate this depression angle change to an elevation change, consider Fig. 8.38 again. Examining two right triangles shows that  $Z = R \sin \psi$  and  $Z - \Delta h = R \sin(\psi - \Delta\psi)$ . Eliminating  $R$  and applying a trigonometric identity gives

$$\begin{aligned} Z - \Delta h &= \frac{Z \sin(\psi - \Delta\psi)}{\sin \psi} \Rightarrow \\ \frac{\Delta h}{Z} &= \frac{\sin \psi - \sin(\psi - \Delta\psi)}{\sin \psi} = \frac{2 \sin\left(\frac{\Delta\psi}{2}\right) \cos\left(\frac{2\psi - \Delta\psi}{2}\right)}{\sin \psi} \end{aligned} \quad (8.78)$$

Assuming  $\Delta\psi$  small and applying a small angle approximation gives

$$\frac{\Delta h}{Z} \approx \frac{\Delta\psi}{\tan \psi} \quad (8.79)$$

Finally, using Eq. (8.79) in Eq. (8.77) gives a measure of the relationship between the change in the IPD for a given pixel and a change in scatterer elevation above the reference plane (Carrara et al., 1995)

$$\Delta h = \frac{\lambda Z \cot \psi}{4\pi B \sin \psi} \Delta\phi_{fg} \quad (8.80)$$

Equation (8.80) is the basic result of IFSAR.